

Extended-Range 5-in Navy Gun: Theoretical Thermal and Erosion Investigations

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Extended-Range 5-in Navy Gun: Theoretical Thermal and Erosion Investigations

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Abstract

Barrel heating and erosion concerns for the Navy are being brought to light by new extended-range munitions. These munitions have, in general, higher performance requirements and use new propellants. In light of these concerns, the following investigation was performed to determine the thermal and erosion characteristics of the current and proposed munitions. In this report, the calculation methodology governing both the thermal and erosion work is described. Six thermal scenarios were computed to compare the thermal load from various combinations of charges. Single-shot erosion predictions are presented for three charges: MK67 with NACO propellant, MK73 with M30A1 propellant, and EX167 extended-range guided munitions (ERGM) propelling charge with EX99 propellant. A fourth single-shot erosion calculation was made using the product gas-state variables and gas velocity of the MK73 charge with chemical constituents of EX99 propellant. The erosion results highlight propellant combustion product differences at the surface between the current and newer propellants. The primary conclusion is that carburization leading to iron carbide formation may be an important contributing factor for much of the material lost from the steel barrel once it is exposed through cracks or chips in the surface coating.

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1. Introduction

The Navy's requirement for extended-range ordnance using shipboard cannons has led to the development of a new 5-in, 62-cal. MK-45, mod-4 gun system capable of firing both conventional ammunition and extended-range guided munitions (ERGM). The methods involved enabling increased range performance are higher muzzle velocity, the inclusion of a rocket in the projectile with tail fins and forward canards, and improved airframe aerodynamics. The requirement to be able to shoot the current ammunition inventory fixed the gun chamber geometry. Several other constraints limited what could be done with the gun mount, barrel, and propelling charge. The length and weight of the barrel were governed by many factors: gun mount slew rate requirements, barrel droop and whip considerations, the physical envelope available onboard ship, blast overpressure effects on ship structures, maximum trunnion loads, recoil load-handling capability, and barrel yield strength, among others. For the propelling charge, since the chamber volume was already fixed, other means were used to achieve higher muzzle velocity: increasing projectile travel due to a longer gun barrel, operating the propelling charge at a higher chamber pressure, and increasing the system chemical energy by utilizing a propellant of greater density and impetus. Unfortunately, the latter usually resulted in an increase in the adiabatic flame temperature of the propellant.

The modifications related to the propelling charge are expected to create an increased thermal load upon the gun and may result in an increase in the erosion rate. Previously, Navy guns were fatigue limited due to the extremely low adiabatic flame temperature of the Navy cool (NACO) single-based propellant. With the newer, higher energy propellant, it is expected that the gun barrel's life will be erosion limited. This report investigates the effects of candidate new charges on the system's thermal load for specific firing scenarios, as well as the erosion differences between the older and newer propelling charges. Navy 5-in gun barrels are normally plated with a 5-mil-thick layer of chrome. While this layer can afford dramatic protection from erosion, it tends to crack, flake, and peel during the first few hundred firings. In the erosion portion of this investigation, the chrome layer was assumed absent.

Historically, the propellant adiabatic flame temperature was used as an indicator of the erosivity of a propellant. Unfortunately, flame temperature was not the only factor [1, 2]. Mitigation of the erosion was a mystery, with the exception of the obvious solution of applying surface coatings or ablatives. Attempts to model erosion using first principles have been and are currently being made [3–6], although it is believed that significant additional work is required to understand the fundamental physics involved.

2. Mechanistic Descriptions

2.1 Heat Transfer. The U.S. Army Research Laboratory (ARL) XBR two-dimensional (2-D) heat-transfer/conduction code used in this report is an extension of the Veritay XBR-2D heat-transfer/conduction code [7, 8] and consists of a 2-D axisymmetric implicit finite-difference heat-conduction model. Required inputs include barrel geometry and physical properties, as well as a single-round interior ballistic history of the propellant product gas velocity, pressure, and temperature.

The inner boundary condition consists of forced convective heat transfer over flat plates [8]

$$-k \frac{\partial T}{\partial r} = h(T_{gas} - T_{wall}), \quad (1)$$

where k is the conductivity, T_{gas} is the combustion product gas temperature, and T_{wall} is the wall temperature. The coefficient h is provided from a correlation of correlations [9] and given as

$$h = 0.037 \frac{\mu^*}{\chi} Re^{*0.8} \frac{C_f}{C_{fi}} C_p, \quad (2)$$

where μ^* is the viscosity computed from a form of Sutherland's law, χ represents the equivalent flat-plate length to the axial position of interest, Re is the Reynolds number, $Re = \chi \rho u / \mu^*$, and C_p is the specific heat of the wall material. The compressible skin friction ratio C_f / C_{fi} , where γ is

the specific heat ratio and M is the Mach number, is given by

$$C_f/C_{fi} = [1 + (\gamma - 1)^2 M^2]^{-0.6}. \quad (3)$$

The outer boundary condition consists of both convective and radiative heat transfer and is expressed as

$$Q_w = h_{conv}(T_{wall} - T_\infty) + \sigma\varepsilon(T_{wall}^4 - T_\infty^4), \quad (4)$$

where ε is the emissivity of the wall, σ is the Boltzmann constant, and T_∞ is the temperature of the surroundings. The convection coefficient, h_{conv} , is represented by one of two models, depending on the value of the Reynolds number. For buoyant laminar flow, the convection coefficient is expressed as

$$h_{conv} = 1.32 \left(\frac{T_{wall} - T_\infty}{OD} \right)^{0.25}, \quad (5)$$

for air, where OD is the outer diameter of the barrel wall. The units are accounted for in the coefficient. For buoyant turbulent cross flow in air, the convection coefficient is

$$h_{conv} = 1.2 (T_{wall} - T_\infty)^{1/3}, \quad (6)$$

where, again, the units are accounted for in the coefficient.

This heat-transfer model has been validated with differing gun systems and differing ammunition, such as 120-mm M256 with M829 [10, 11] and M865 [10, 11]; 155 mm with M203 [8], MACS, [12] and LP zones 1–7 [13]; 25-mm Bushmaster with M919 and M791 [14]; and 27-mm caseless [8]. The results agree with the experimentally measured values.

2.2 Erosion Methodology. The erosion representation consists of three fully coupled portions, including thermal ablation and heat conduction with an iterative solution for the surface regression, independent heat and multicomponent species mass transport to the surface, and full equilibrium thermochemistry. The contributions due to mechanical wear and abrasion, however, are not included. A surface control volume treatment is also included to ensure conservation of mass of the solid-phase product species due to the solid-gas interface. The core flow gas-phase velocity, as well as state variables pressure and temperature of the gun tube from the XKTC [15] or NGEN [16] interior ballistic codes are used, as well as species data from IBBLAKE [17–19]. The thermochemistry calculation incorporates the NASA Lewis [20] thermochemical database. Primary features of the model have been described [6, 13] and are cursorily presented here.

The model, shown conceptually in Figure 1, enables the surface to heat convectively. A surface control volume is defined, and surface reactions occur, which release additional energy into the system as a surface source term. Various gas, solid, or liquid products are produced, which either remain as solids or are removed in the case of gases and liquids.

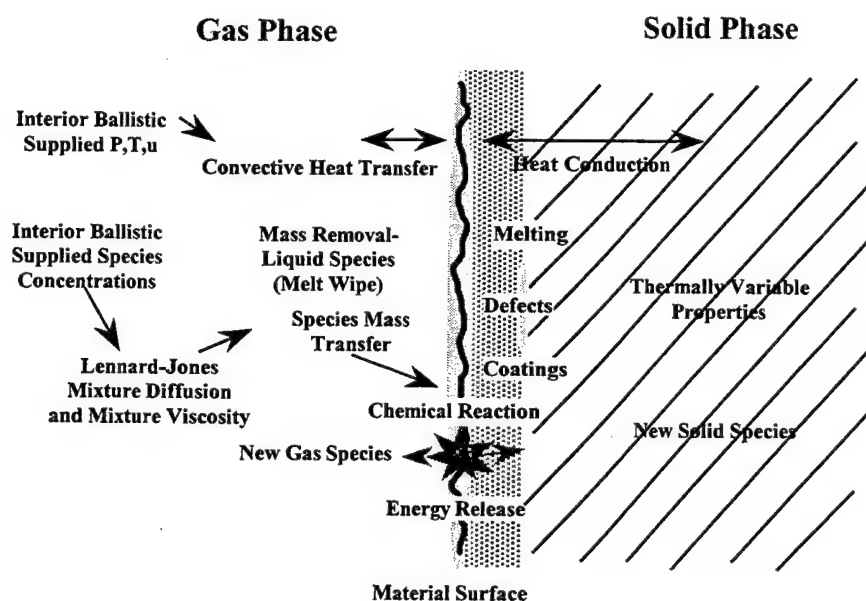


Figure 1. Conceptual Tube Surface Illustration.

The in-depth temperature response of the unablated (solid) material is modeled using the one-dimensional (1-D) heat conduction equation:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{1}{r^\beta} \frac{\partial}{\partial r} \left(r^\beta k \frac{\partial T}{\partial r} \right). \quad (7)$$

By setting $\beta = 0$ or $\beta = 1$, the planar or axisymmetric form of the governing equation can be obtained. The relevant material properties are density, ρ ; specific heat, C_p ; and conductivity, k . The conductivity and specific heat vary with temperature.

The surface energy balance, while gross melting is not occurring, includes the same convective surface heat input used in the thermal calculations, along with the possible contribution due to the surface reaction (shown in equation 8). This source term is balanced with the energy conducted through the material:

$$h (T_{gas} - T_{wall}) = -k \frac{\partial T}{\partial r} + Source. \quad (8)$$

However, when the system is melting, the energy balance includes the fixed surface temperature condition, as well as the unknown surface location. The surface temperature cannot rise beyond the specified melting value because any additional energy is applied to the material-phase transition (melting) as shown:

$$T_{wall} = T_{melt}, \quad \rho L \frac{\partial s}{\partial t} = h (T_{gas} - T_{wall}) + k \frac{\partial T}{\partial r} - Source. \quad (9)$$

Prior to the onset of melting, the governing equations and boundary conditions are linear, and solutions are obtained in a direct (noniterative) fashion. During the melting process, the equations become nonlinear since the computational domain dimensions are coupled to the regression rate. An iterative approach is utilized during melting to address the nonlinearity. Because the boundary of the computational domain moves during the erosion event, a

transformed version of the governing equation is employed. This allows the equations to be solved in a fixed computational space, even though the physical boundary is moving. A generalized transformation between the computational coordinate, ξ , and the physical coordinate, r , is utilized, as shown in the transformed equations:

$$\rho C_p \left(\frac{\partial T}{\partial t} + \xi_t \frac{\partial T}{\partial \xi} \right) = \frac{1}{r} \xi_r \frac{\partial}{\partial \xi} \left(r k_r \frac{\partial T}{\partial \xi} \right),$$

$$\xi_t = \frac{-r_t}{r_\xi} \equiv \frac{\partial r}{\partial t} \frac{\partial \xi}{\partial r},$$

and

$$\xi_r = \frac{1}{r_\xi} \equiv \frac{\partial \xi}{\partial r}. \quad (10)$$

In this form, the nonlinear nature of the governing equation produced by the moving boundary is evident because the metric terms, ξ_r and ξ_t , are not constant and are dependent on the erosion rate when the grid is moving. This methodology compares very well to the semi-analytical solutions of Landau in test cases [20].

The species mass transport to the surface from the core flow of the propellant product gases is assumed frozen and is provided through a concentration potential $\phi_{i \text{ core-flow}} - \phi_{i \text{ wall}}$ for each species i , and a mass transport coefficient h_m derived from Sherwood number correlations integrated over space and time [6]:

$$Mass_i = \iint h_m (\phi_{i \text{ core-flow}} - \phi_{i \text{ wall}}) dA dt. \quad (11)$$

The surface control volume reaction is governed by equilibrium kinetics because the actual reactions and rates are not well known at this time. Equilibrium chemical processes are considered to dominate whenever the characteristic time for a fluid element to traverse the flow field of interest is much longer than the characteristic time for chemical reactions to approach

equilibrium. As the pressure and temperature increase, the molecular collision frequency and energy per collision increases, leading to smaller characteristic chemical times, and the chemical processes approach equilibrium.

The condition for chemical equilibrium may be stated as the minimization of the Gibbs free energy [21]. For a mixture of N species (e.g., atoms or molecules) with the number of moles of species denoted as n_i , the Gibbs free energy per mole of mixture is given in terms of the Gibbs free energy of the individual species, g_i ; the internal energy, e ; the temperature, T ; the entropy, s ; the pressure, p ; and the specific volume, v :

$$G = \sum_{i=1}^N n_i g_i = e - Ts + pv. \quad (12)$$

2.3 Surface Description. The full equilibrium control volume approach, as shown in Figure 2, results in many product mass fractions that are physically impossible due to the constraints of diffusion into the solid phase. Mainly, the carbon that results from CO and/or CO₂ breakdown will react with as much iron as possible to form Fe₃C if permitted. To treat this deficiency, the amount of carbon available for a reaction with the steel is diffusion limited.

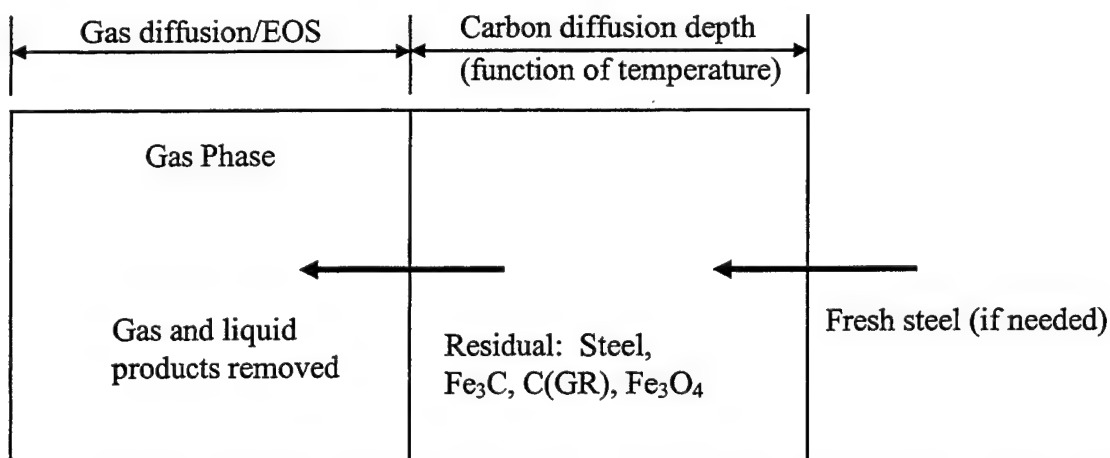


Figure 2. Control Volume Description Showing Solid-Phase Dependence Upon Carbon Diffusion Depth.

A surface exposed to a carbon concentration G per unit surface area for a specified length of time t has a carbon concentration $C(x)$ at a specified depth of x given by the following relationship:

$$C(x) = \frac{G}{\sqrt{\pi Dt}} e^{\frac{-x^2}{4Dt}}, \quad (13)$$

where D is the diffusion coefficient over the α and γ phases (body-centered cubic [BCC] and face-centered cubic [FCC] lattice structure, respectively). The diffusion of carbon into α iron ($T < 1,118^\circ\text{C}$) is given by the following function in *Smithells Metals Reference Handbook* [22] in square centimeters per second, where R_u is the universal gas constant in (kilo-calories per mole per Kelvin):

$$D = 0.008e^{\frac{-19.8}{R_u T}} + 2.2e^{\frac{-29.3}{R_u T}}, \quad (14)$$

while the diffusion of carbon into γ iron ($T < 1,300^\circ\text{C}$) is provided by

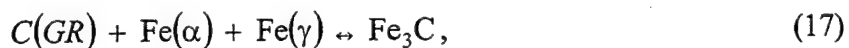
$$D = 0.36e^{\frac{-36}{R_u T}}. \quad (15)$$

To find the total amount of carbon that has diffused in time t , the concentration function can be integrated and has an error function solution as

$$\int_0^x C(x) dx = \frac{G}{\sqrt{\pi Dt_0}} \int_0^x e^{\frac{-x^2}{4Dt}} dx = G(\text{erf}(x)). \quad (16)$$

Integrating the concentration profile to the maximum depth to which material can diffuse in time t provides the carbon diffused into the material over the time period. To treat the reactant products from the full equilibrium calculation, a subset reaction is created consisting of the

carbon, iron (α) and iron (γ), and iron carbide. The total carbon available for reaction is equal to the diffused carbon plus the residual carbon in solid from the original steel or carbon in the form of iron carbide, as well as the possible carbon on the surface:



where $Fe(\alpha)$ or $Fe(\gamma)$ are supplied as fresh material as needed, depending upon the control volume temperature. The product carbon, in the solid portion of the control volume, $C(GR)$, and Fe_3C from the previous time step are retained as residuals and reintroduced as reactants in the next time step unless the surface temperature is over the melting point of Fe_3C , in which case the carbide is removed. If there is no excess carbon, then $Fe(\alpha)$ or $Fe(\gamma)$, depending on the temperature, is carried over to the next time step. Once the post-equilibrium calculation is made, the final energy change in the control volume is recomputed and the amount attributable to the residual solids is accounted for as the surface energy source term. Oxide formations are treated similarly.

2.4 Erosion Calculations. Four Navy propelling charges were modeled, as presented in Table 1. The first three (EX167, MK73, and MK67) have been fired in the cannon specified. The fourth round (EX9973) is a numerical experiment of a hypothetical propelling charge using EX99 propellant with a MK92 projectile in the 5-in/62-cal. gun, with matching ballistics characteristics to the MK73 charge in the same gun. This charge provides an interesting comparison to the standard MK73 charge since the ballistic performance, total system chemical energy, and propellant flame temperatures are very similar, while the concentrations of certain propellant combustion species differ substantially. Namely, for the M30A1, the principle combustion product is N_2 , while for the EX99, it is CO. Normally, the MK73 charge includes a TiO_2 /wax wear-reducing liner that tends to reduce the heat transfer to the barrel somewhat; however, the liner was not included in this investigation.

Please note that the caliber of the cannon includes between 35 and 40 in of chamber, so the travel is not the length of the tube. Each of these rounds was modeled using XKTC and

Table 1. Modeled Propelling Charges

Propelling Charge	Propellant/ Weight (lb)	Adiabatic Flame Temp. (K)	Projectile/ Weight (lb)	Peak IB Pressure (psi)	Muzzle Velocity (ft/s)	Cannon (in/cal.)
EX167	EX99/26.50	~3,010	ERGM/110	67	2,812	5/62
MK73	M30A1/21.26	~3,040	MK109/68.2	55	3,098	5/62
MK67	NACO/20.78	~2,285	MK92/70.0	52	2,791	5/62
EX9973 Num. Exp.	EX99/20.00	~3,010	MK109/68.2	54	3,105	5/62

IBBLAKE to obtain gas state and velocity data, as well as the thermochemical constituents for each charge.

The single-shot inner surface peak temperatures are presented in Figure 3 for the four rounds modeled in Table 1. As expected, the EX167 charge with the EX99 propellant had the highest inner surface temperature of about 1,625 K at 43 in from the rear face of the tube (RFT), while the MK67 propelling charge with the NACO propellant had the lowest inner surface temperature of about 1,210 K at 40.9 in from RFT. The surface temperatures for both the MK73 and altered propellant MK73 were between the MK67 and EX99 temperatures, with a peak of about 1,575 K at 40.9 in from RFT. Note that these wall surface temperatures are only short-lived transients that decay to much lower "residual" temperatures within seconds of the firing as the energy diffuses into the gun tube.

The erosion predictions in Figure 4 highlight not only the surface temperature effects on erosion but also the propellant combustion product differences at the bore surface for each of the three propellants. The results are fairly consistent with the rule of thumb concerning barrel surface and adiabatic flame temperatures, where the EX167, MK73, and MK67 propelling charges exhibit a decreasing trend in material lost. Perhaps the most interesting result occurred when the chemistry from a matching pressure and velocity EX99 charge of the MK73 charge was placed into the MK73 erosion calculation. Figure 4 demonstrates an increase in erosion of about 15%, not accounted for through surface temperature changes, but rather through species

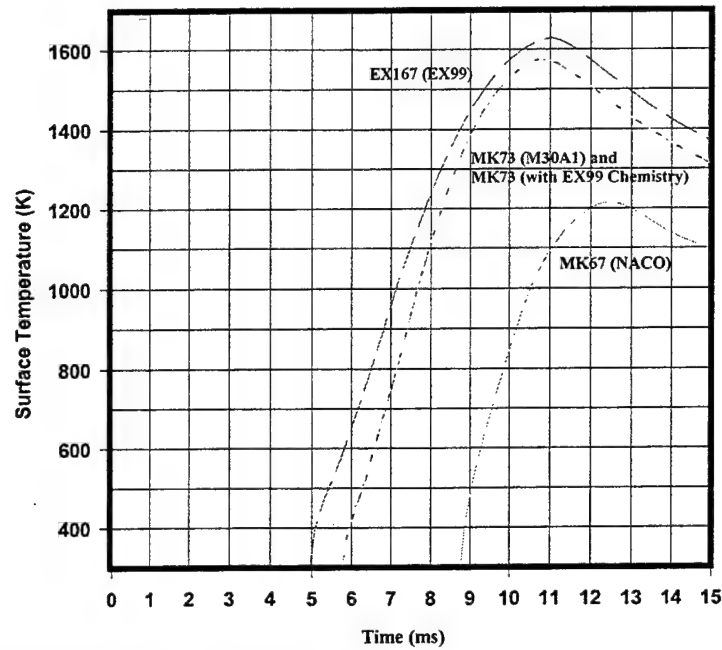


Figure 3. Single-Shot Surface Temperatures for MK67, MK73, EX167, and MK73 With EX99 Rounds. (All Are at 40.9 in From RFT, Except the EX167, Which Is at 43 in.)

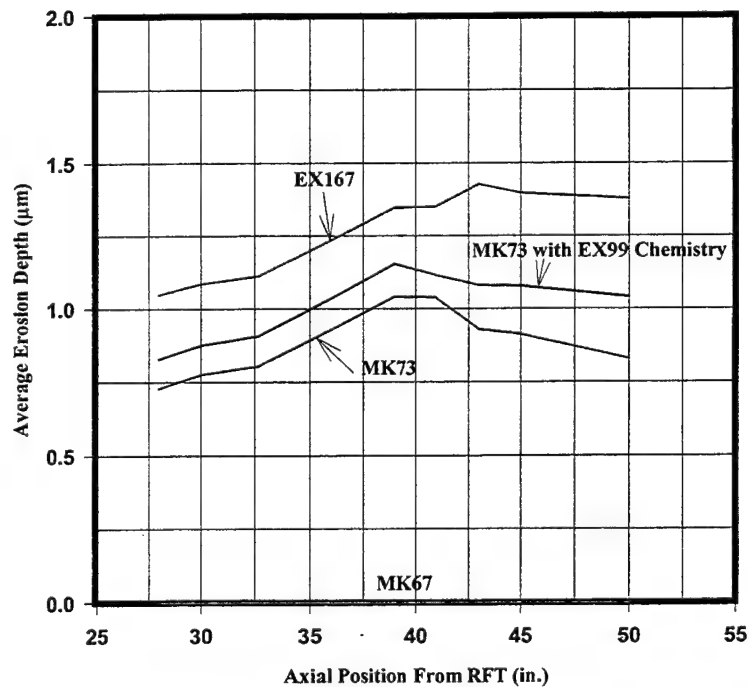


Figure 4. Single-Shot Surface Regression for MK67, MK73, EX167, and MK73 With EX99 Rounds.

concentration differences in the combustion products of EX99 propellant and M30A1 propellant. Given that none of these charges cause the surface to exhibit gross melting of the original gun steel material (i.e., the bore temperature never reaches the melt temperature), the mechanism described for the material loss (i.e., removal of the carbide formed) is controlling the erosion rate.

2.5 Thermal Calculations. For the thermal scenario investigations, six firing scenarios are specified in Table 2 with a mix of rounds. Each scenario was computed assuming that the charge case was nonexistent, and the rounds are ordered as shown in the table. The EX167 propelling charge must be double-rammed with the long rocket-assisted projectile rammed in the first cycle, and the propelling charge must be rammed separately in the second cycle. Maximum firing rate for these rounds that are in the ready service drum is about 9 rounds/min. After this supply is depleted, rounds must be taken from the magazine and hand loaded into the ready-service drum. This reduces the effective firing rate for following rounds to about 4 rounds/min.

Table 2. Six Firing Scenarios for Thermal Considerations

Scenario No.	Type of Prop. Charge	No. of Rounds	Firing Rate (rounds/min)	Round Location
1	EX167	10	9	In ready-service drum
	EX167	240	4	From storage
	MK67	250	10	From storage
2	MK67	20	18	In ready-service drum
	MK67	230	10	From storage
	EX167	250	4	From storage
3	MK67	10	10	From storage
	EX167	10	4	From storage
Continue sustained firing, alternating propelling charge type every 10 rounds until 250 of each charge has been fired.				
4	MK 67	600	10	From storage
5	EX 167	600	4	From storage
6	MK 73	600	10	From storage

The MK67 and MK73 propellant charges are single-rammed, so the maximum firing rate for rounds that are in the ready service drum is 18 rounds/min. After this supply is depleted, rounds must be taken from the magazine and hand loaded into the ready service drum. This reduces the effective firing rate for following rounds to about 10 rounds/min.

Scenario nos. 1-3 involve mixed ammunition and mixed firing rates presented in Figures 5-7. Figure 5 demonstrates the effect of firing rate on temperature increase. As the firing rate changes from 9 rounds/min to 4 rounds/min, the temperature quickly responds by dropping a little, producing a small spike or sawtooth. When the firing rate is once again increased to 10 rounds/min, the temperature profile responds again by jumping up about 20 K, until settling into a new heating profile. The peak temperatures experienced at the end of this scenario are about 1,025 K. The temperature history for scenario no. 2 shown in Figure 6 is somewhat the inverse of scenario no. 1 in that the firing rate is more rapid at the beginning and then slows down. This gives the energy more time to soak through the cannon and assist in removing the energy in external convection by having the external temperature difference higher for a longer period of time; thus, the final temperatures are slightly lower than scenario no. 1 at about 1,000 K. Scenario no. 3 involves an even mixing of the firing rates and charges. It also produces what appears to be the worst of the first three scenarios, with a final temperature of between 1,150 K and 1,250 K. The sawtooth effect presented is also seen in scenario no. 1 during the change from 4 rounds/min to 10 rounds/min, with a similar jump in temperature. This effect is coupled to the uniformity of the temperature throughout the barrel. The radial temperature profile does not settle into a steady increase in temperature (i.e., a top-hat profile) for scenario no. 3, but rather is continuously driven to higher differentials between the outer and inner temperatures, thus resulting in higher inner surface temperatures.

The results of the calculations for scenario nos. 4-6 are presented in Figures 8-10. The inner surface temperature for the nominal MK67 NACO charge rises over the 600 rounds, at 10 rounds/min, to about 1,000 K in Figure 8. Figure 9 shows that the temperature of the cannon rises to about 1,050 K at the case mouth for the EX167 charges. Figure 3 shows that the single-shot peak temperature is highest for the EX167 charge (EX99 propellant). An explanation for

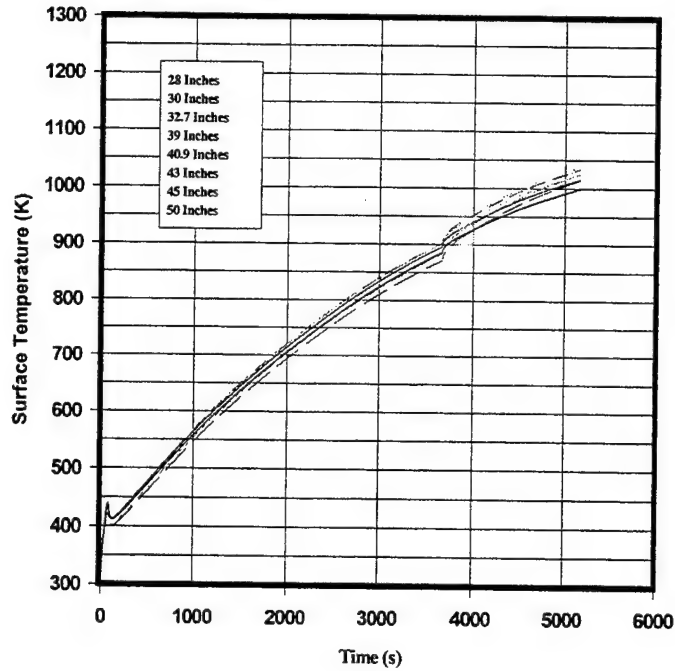


Figure 5. Inner-Bore Residual Surface Temperatures for Scenario No. 1: 10 EX167 Rounds at 9 Rounds/min, Followed by 240 EX167 Rounds at 4 Rounds/min, Followed by 250 Rounds of MK67 at 10 Rounds/min.

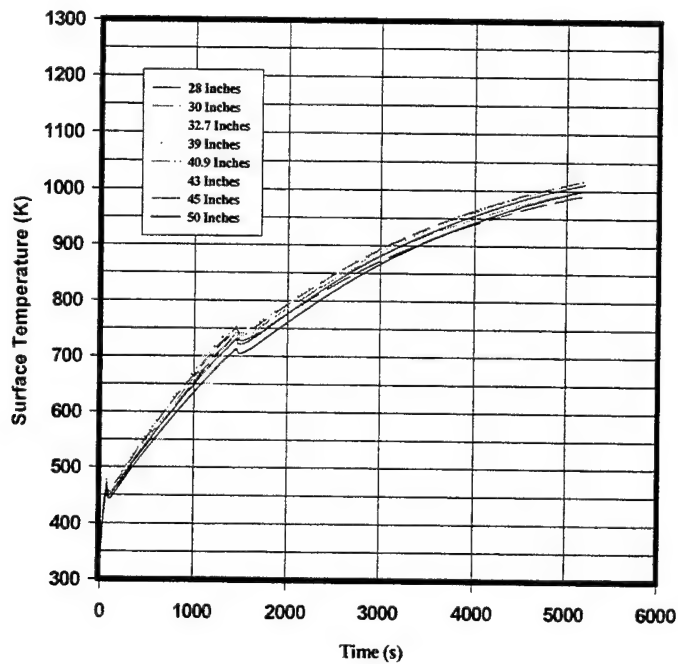


Figure 6. Inner-Bore Residual Surface Temperatures for Scenario No. 2: 20 MK67 Rounds at 18 Rounds/min, Followed by 230 MK67 Rounds at 10 Rounds/min, Followed by 250 Rounds of EX167 at 4 Rounds/min.

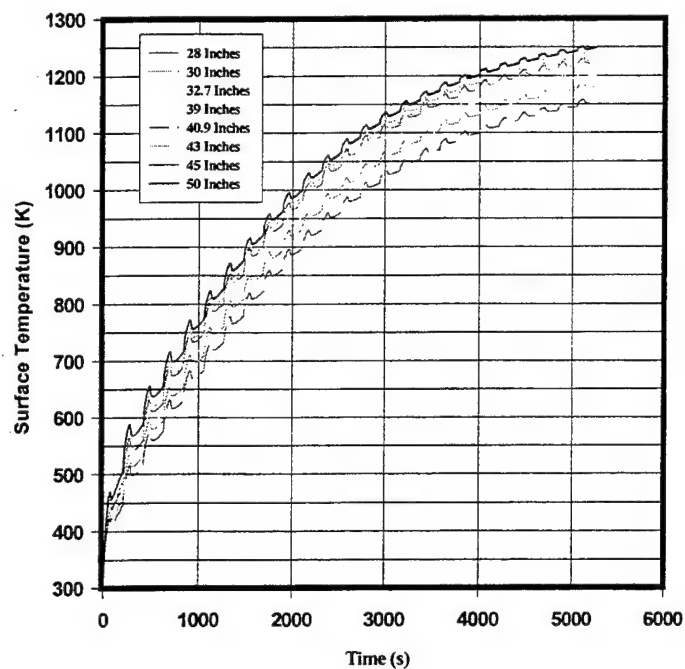


Figure 7. Inner-Bore Residual Surface Temperatures for Scenario No. 3: 10 MK67 Rounds at 10 Rounds/min, Followed by 10 EX167 Rounds at 4 Rounds/min, Alternating Until 500 Total Rounds Are Fired.

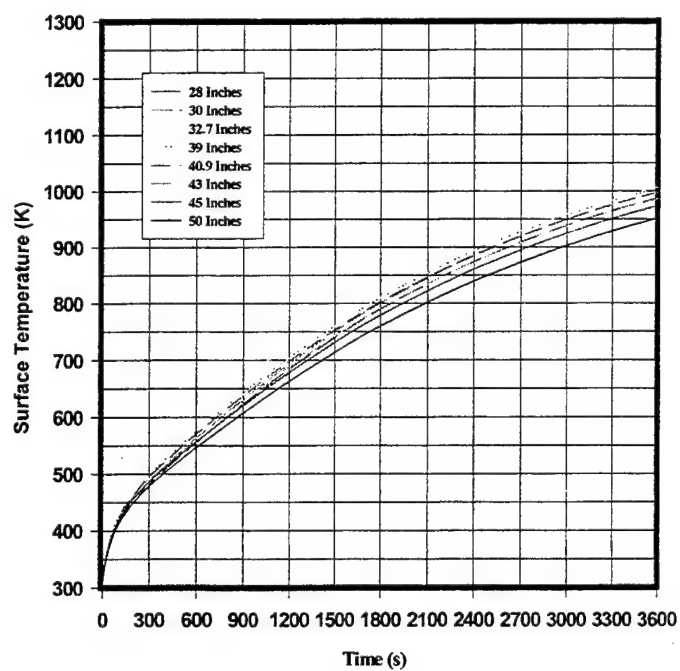


Figure 8. Inner-Bore Residual Surface Temperatures for Scenario No. 4: 600 MK67 Charges at a Firing Rate of 10 Rounds/min.

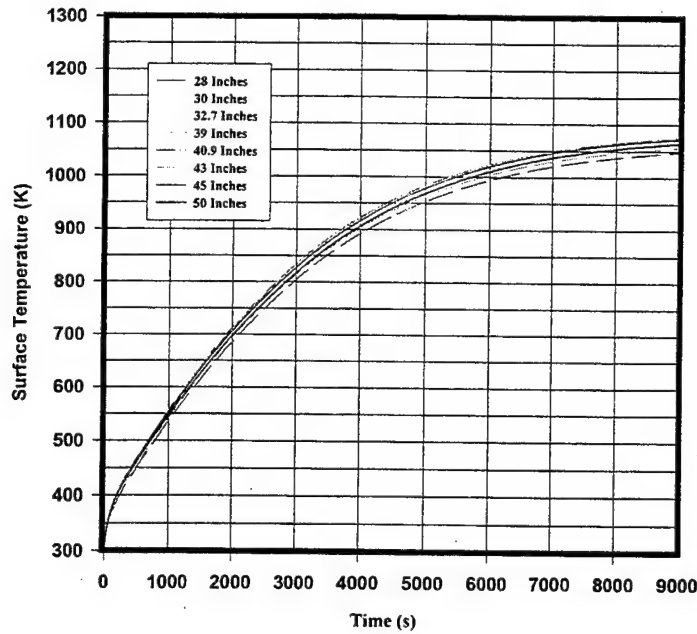


Figure 9. Inner-Bore Residual Surface Temperatures for Scenario No. 5: 600 EX167 Charges at a Firing Rate of 4 Rounds/min.

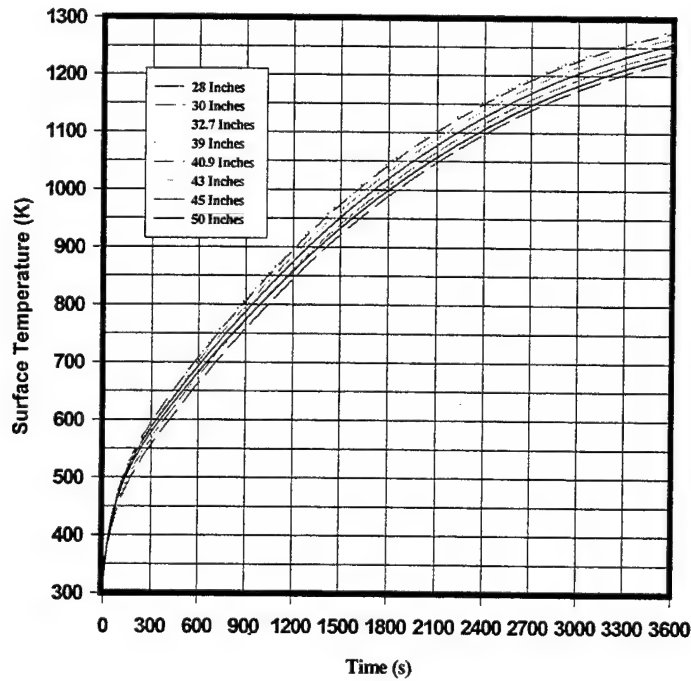


Figure 10. Inner-Bore Residual Surface Temperatures for Scenario No. 6: 600 MK73 Charges at a Firing Rate of 10 Rounds/min.

why the higher flame temperature EX99 propellant and the low-temperature NACO propellant produce very nearly the same peak residual bore temperatures in the firing scenarios is that the reduced firing rate of the EX167 round due to double ramming reduces the overall thermal burden on the cannon. Figure 10 presents the MK73 M30A1 propellant scenario of 600 rounds at 10 rounds/min. Of these three scenarios, this one has the highest temperature in the region of the case mouth, about 1,250 K.

Any potential discrepancy between these computed scenarios and existing experimental data is most likely due to potential inaccuracies in the external heat-transfer coefficient. The coefficients chosen may not be applicable when the external temperatures becomes as high, as in these scenarios under these extreme firing and thermal-loading conditions. Also, it must be noted that, even at these high temperatures, there will still be a temperature gradient from the inner wall temperature plotted herein to the outer wall temperatures measured elsewhere over a long firing scenario.

3. Conclusions

The primary conclusion concerning the erosion potential for the charges is that, although the flame temperature is about the same for the EX99 propellant and M30A1 propellants, their erosivity appears to be much different because of the product species. In M30A1, the primary product species is N_2 , while EX99 has carbon monoxide as the principal product species. Carbon monoxide degenerates on the surface and is the principle source of carbon for iron carbide formation. These results stress the importance of developing an effective wear-reducing agent for the EX167 propelling charge. The Navy is currently evaluating such agents in the form of conventional TiO_2 /wax wear-reducing liners and ablative paste.

The predominate erosion mechanism proposed states that carburization leading to iron carbide formation may be an important contributing factor for much of the material lost from the steel barrel once it is exposed through cracks or chips in the surface coating. Iron carbide melts at about 1,423 K as opposed to gun steels, which typically melt above 1,700 K.

The EX167 round may not load the cannon thermally more than it already is with the MK67 NACO charge. The MK73 charge loads the cannon much more severely than either of the other two.

The results obtained in this investigation have not been validated experimentally. It is unlikely that they can be, as it becomes cost-prohibitive to manufacture components and conduct a test of the magnitude required to study these effects.

Future work may focus on adding species chemistries to simulate the effect of an ablative layer that has been deposited on the inner bore surface of the gun barrel.

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